

# **QCD Phase Boundary and the Critical Point**

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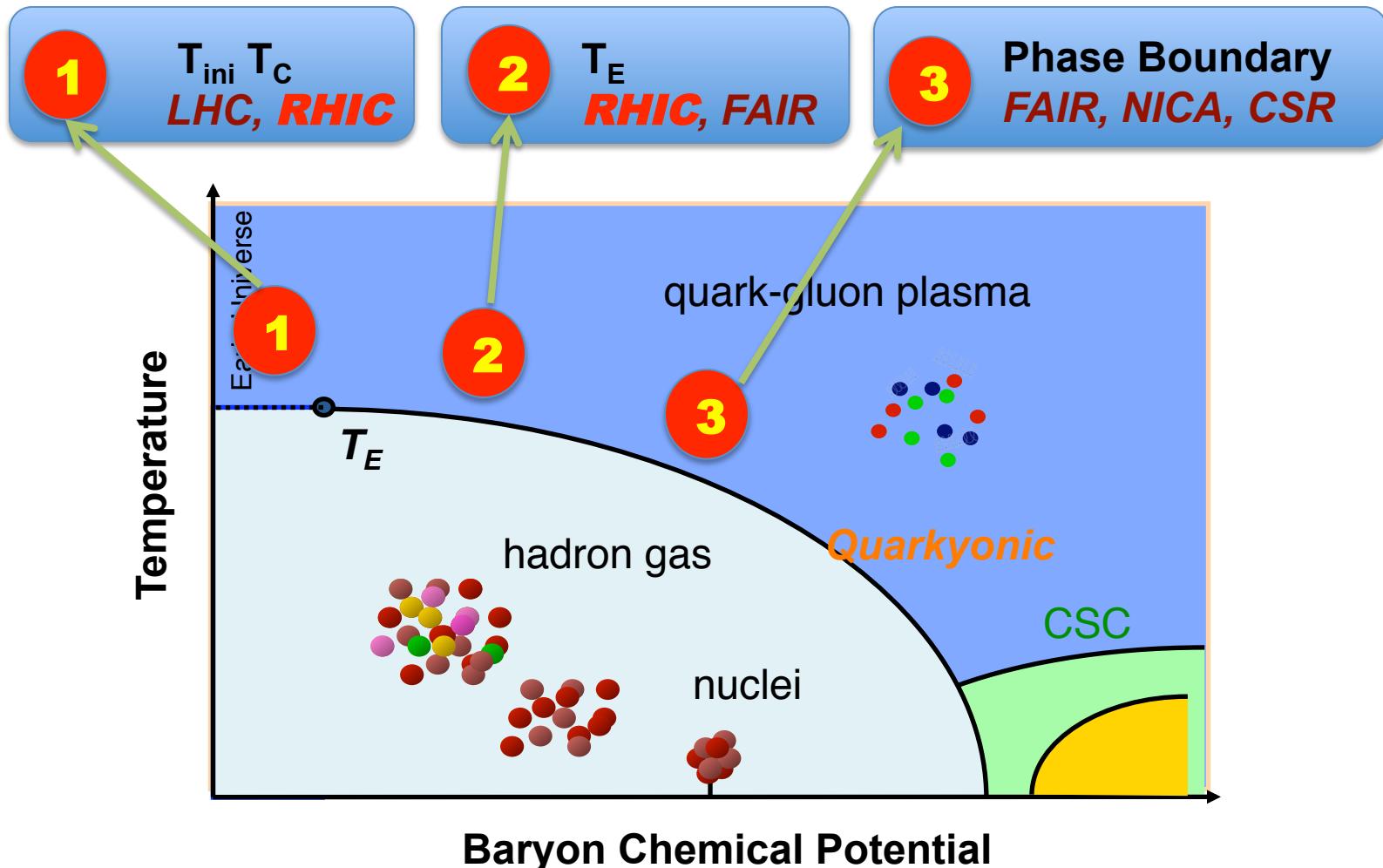
*Many Thanks to the Organizers!*



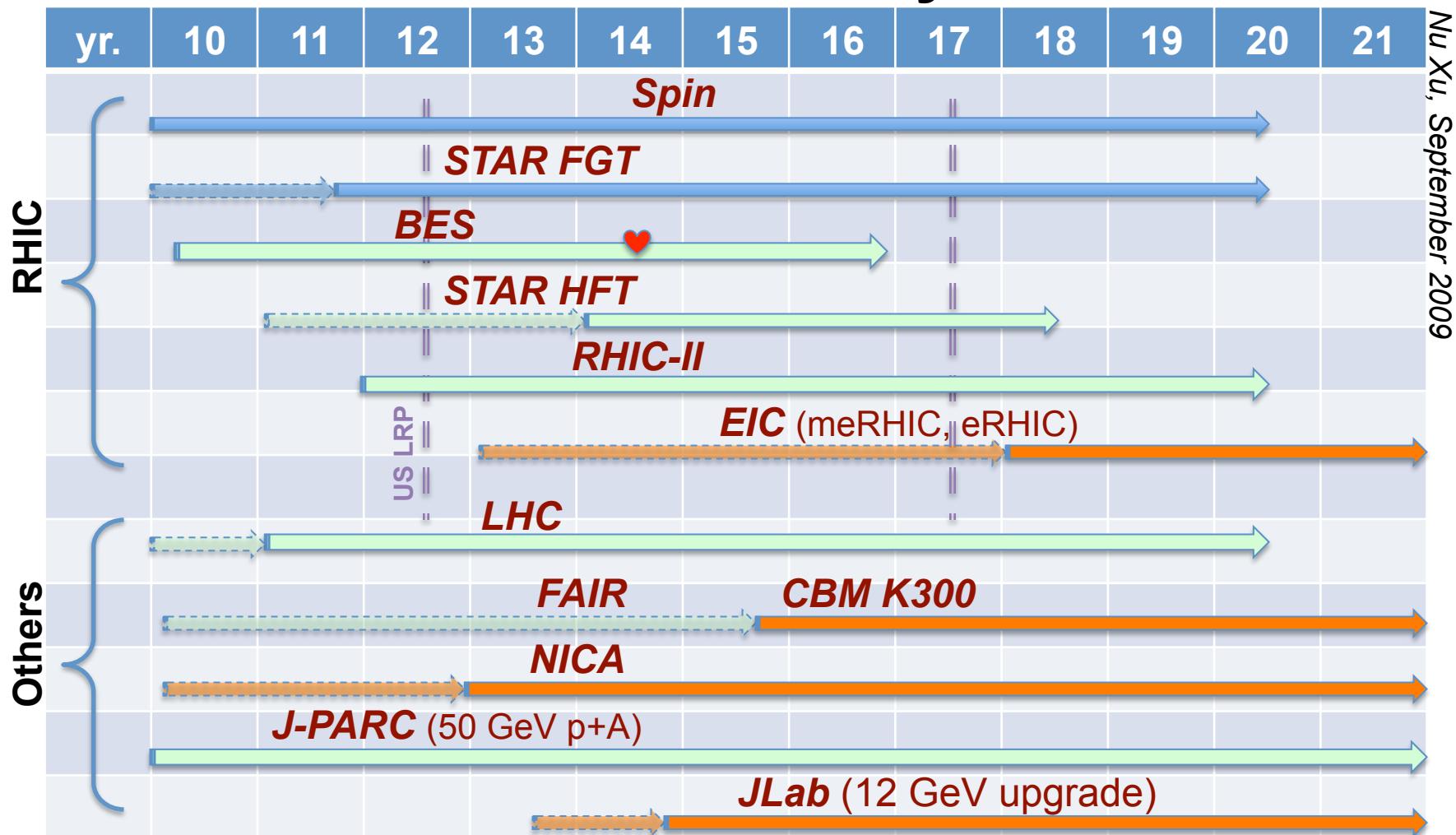
U.S. DEPARTMENT OF  
**ENERGY**



# The QCD Phase Diagram and High-Energy Nuclear Collisions



# Timeline of QCD and Heavy Ion Facilities



- Spin
- Heavy Ion
- R&D
- Future programs



# STAR Physics Focus

***Structure of Nucleon***

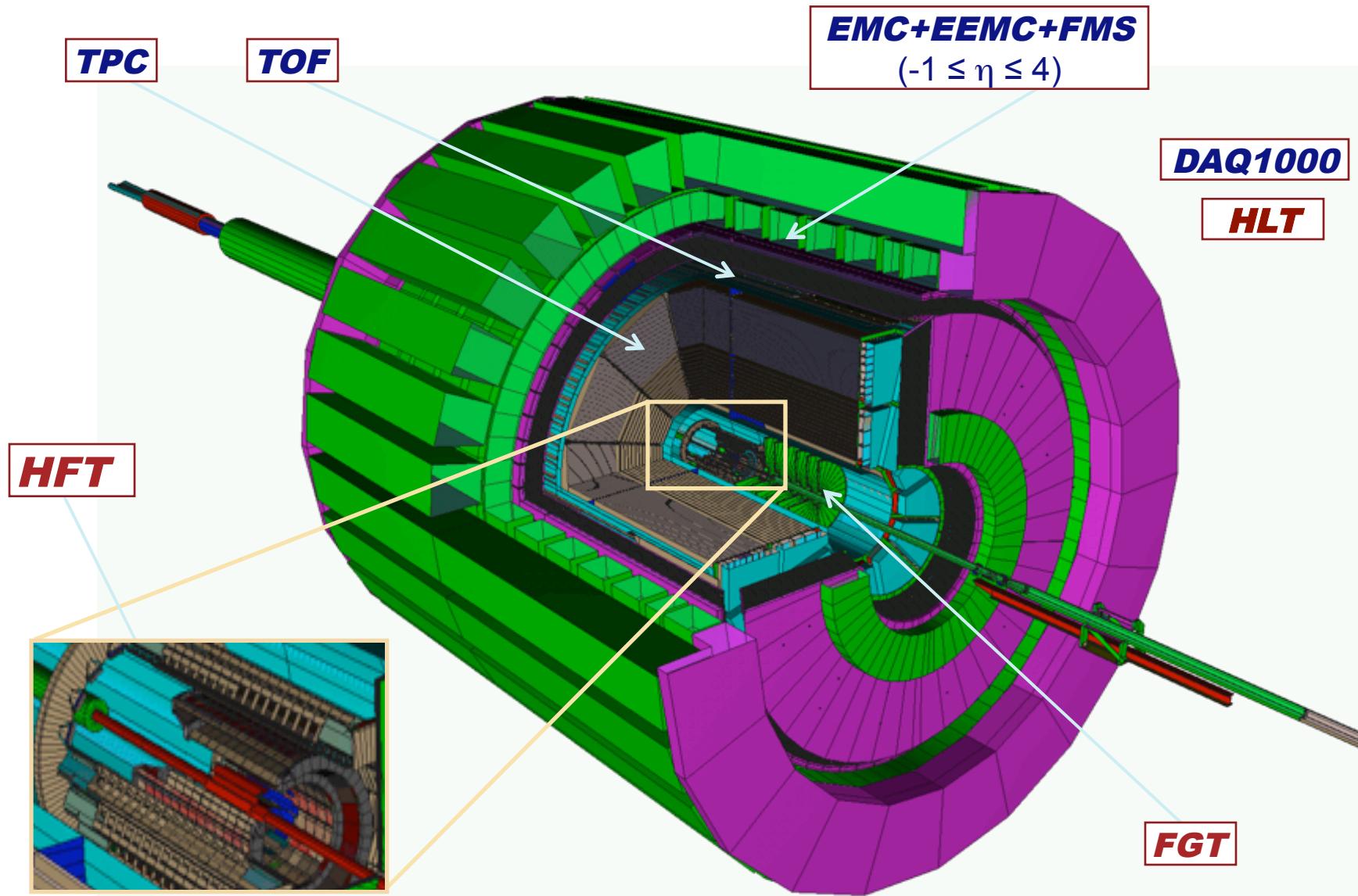
***Structure of Cold Nuclear Matter***

***Structure of the Hot Matter***

***Partonic degrees of freedom &  
QCD***



# STAR Detectors: Full $2\pi$ particle identification!





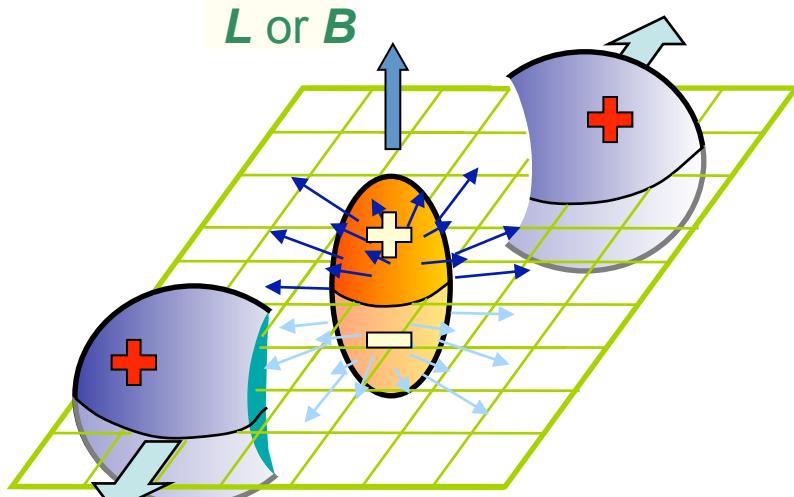
# Outline

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- (1) Introduction
- (2) Recent results from RHIC
- (3) A proposal: using high moments for locating the possible QCD critical point
- (4) Summary and Outlook

# Search for Local Parity Violation

## in High Energy Nuclear Collisions



*The separation between the same-charge and opposite-charge correlations.*

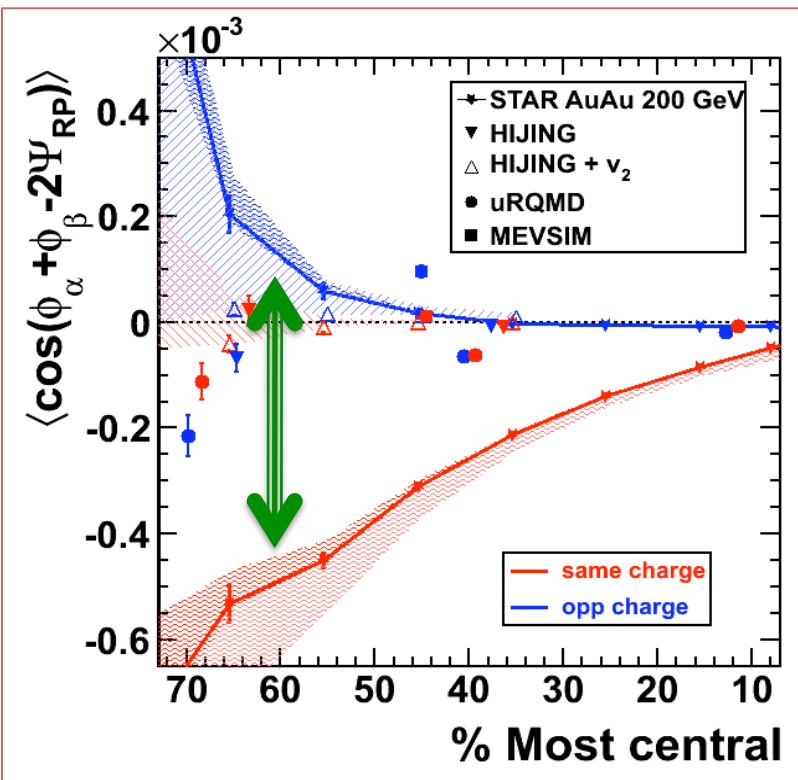
- Strong external EM field
- De-confinement and Chiral symmetry restoration

$$\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle$$

Parity even observable

Voloshin, PR C62, 044901(00).

STAR; arXiv: 0909.1739 (PRL); 0909.1717 (PRC).

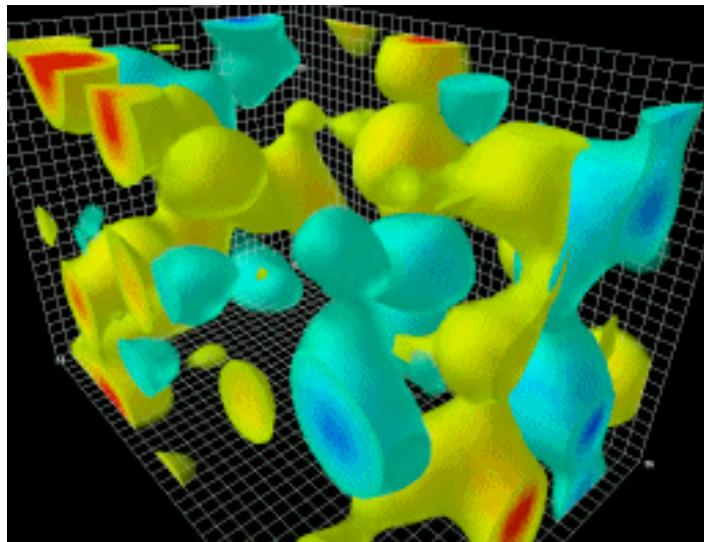


# Search for Local Parity Violation

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## in High Energy Nuclear Collisions

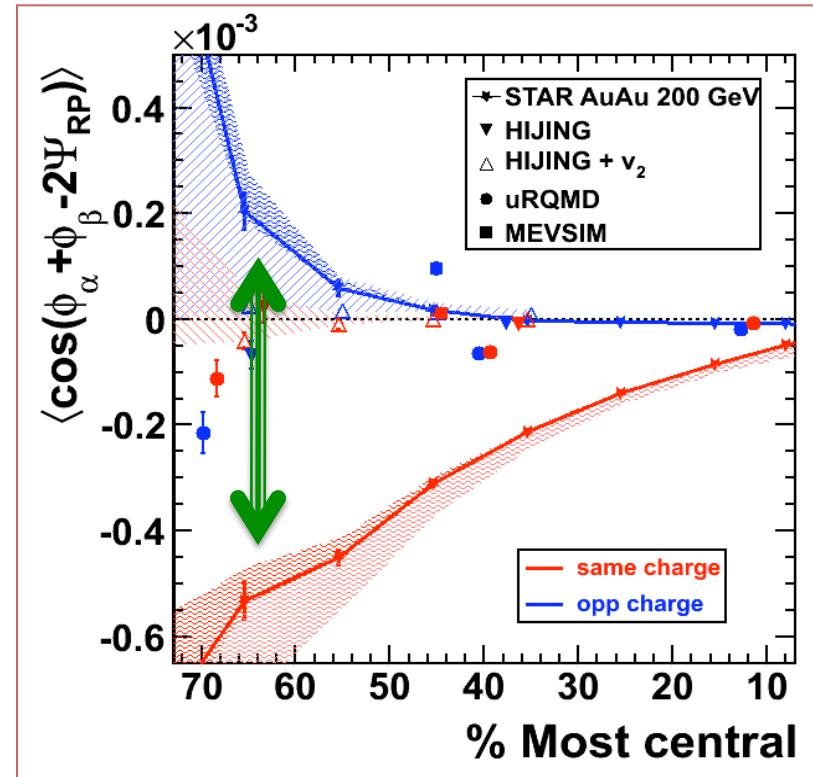
Animation by Derek Leinweber



### Chiral Magnetic Effect:

- Kharzeev, PL B633 260 (2006).  
Kharzeev, Zhitnitsky, NP A797 67(07).  
Kharzeev, McLerran, Warringa, NP A803 227(08).  
Fukushima, Kharzeev, Warringa, PR D78, 074033(08).

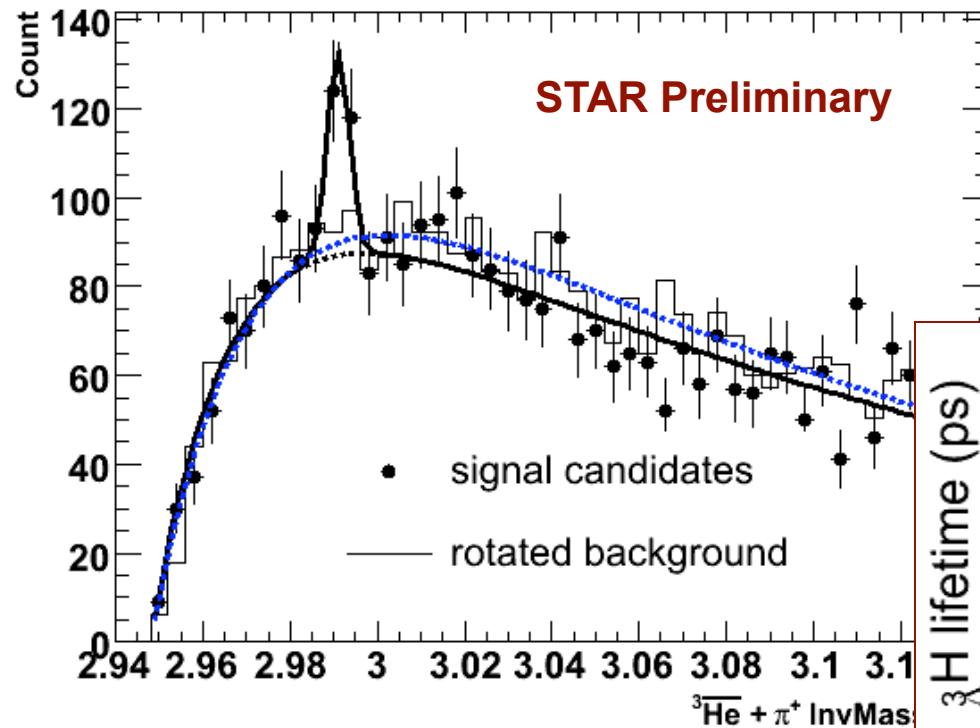
Topological transitions have never been observed *directly* (e.g. at the level of quarks in DIS). An observation of the *spontaneous strong* parity violation would be a clear proof for the existence of such physics.



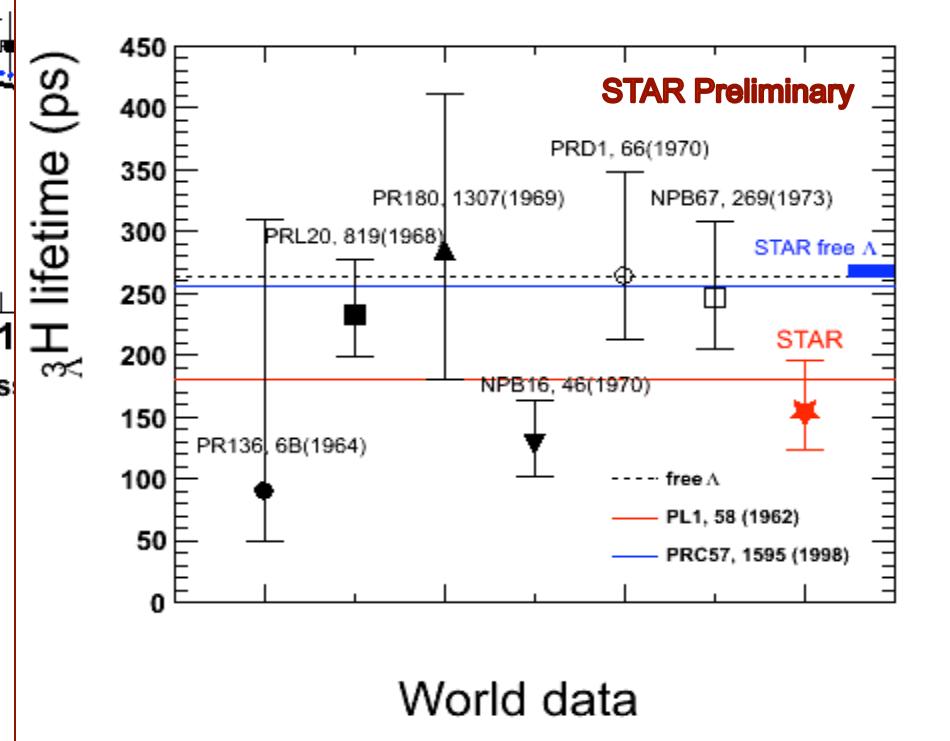


# First Observation of $\bar{\Lambda} \rightarrow {}^3\bar{H} e + \pi^+$

AuAu200\_Combined\_Anti- ${}^3\bar{H}$ \_candidate



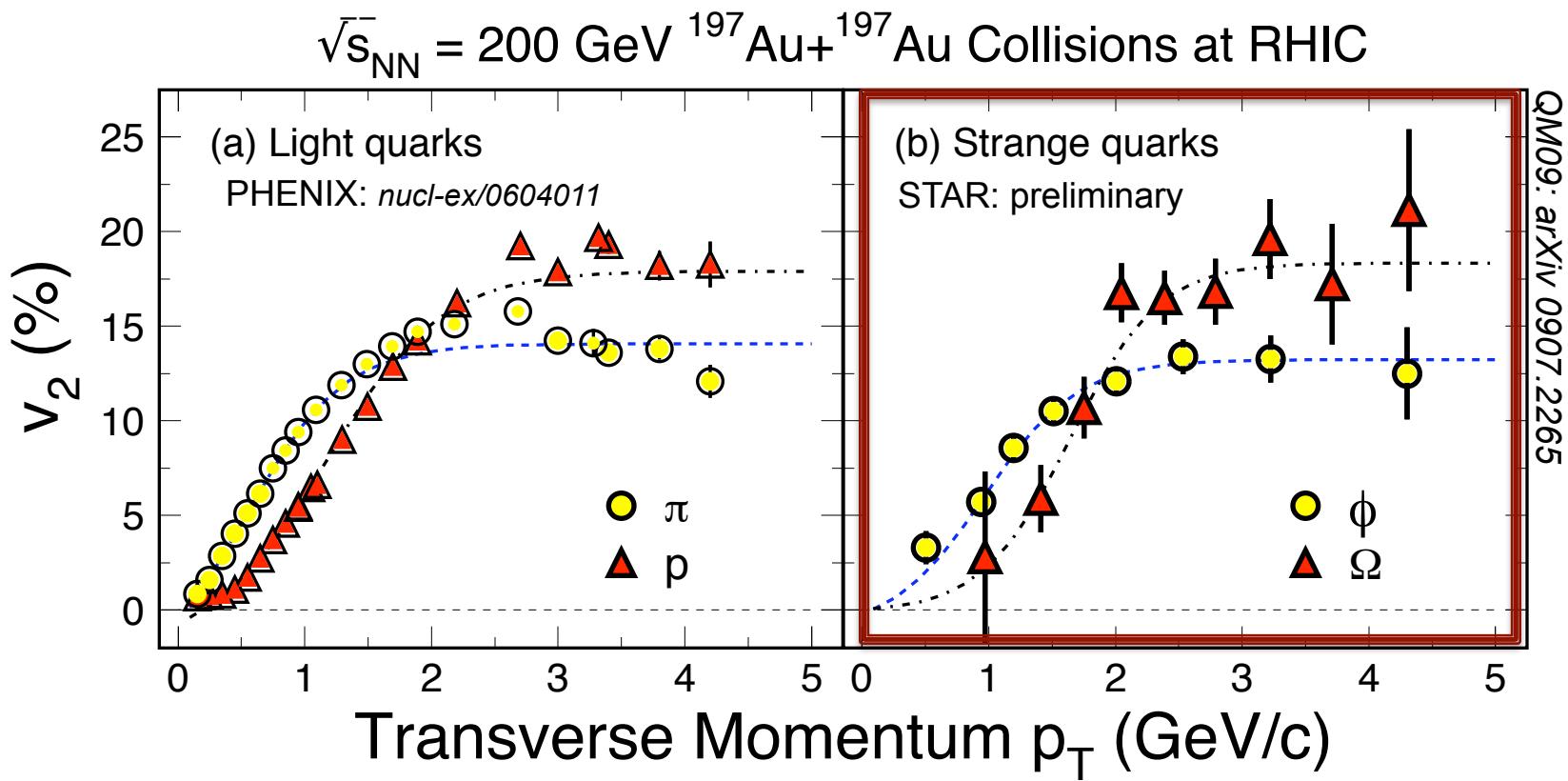
200 GeV Au+Au collisions at RHIC



First observation of  
**an anti-hypernucleus**

To be submitted to **Science** magazine

# Partonic Collectivity at RHIC



Low  $p_T$  ( $\leq 2 \text{ GeV}/c$ ): hydrodynamic mass ordering

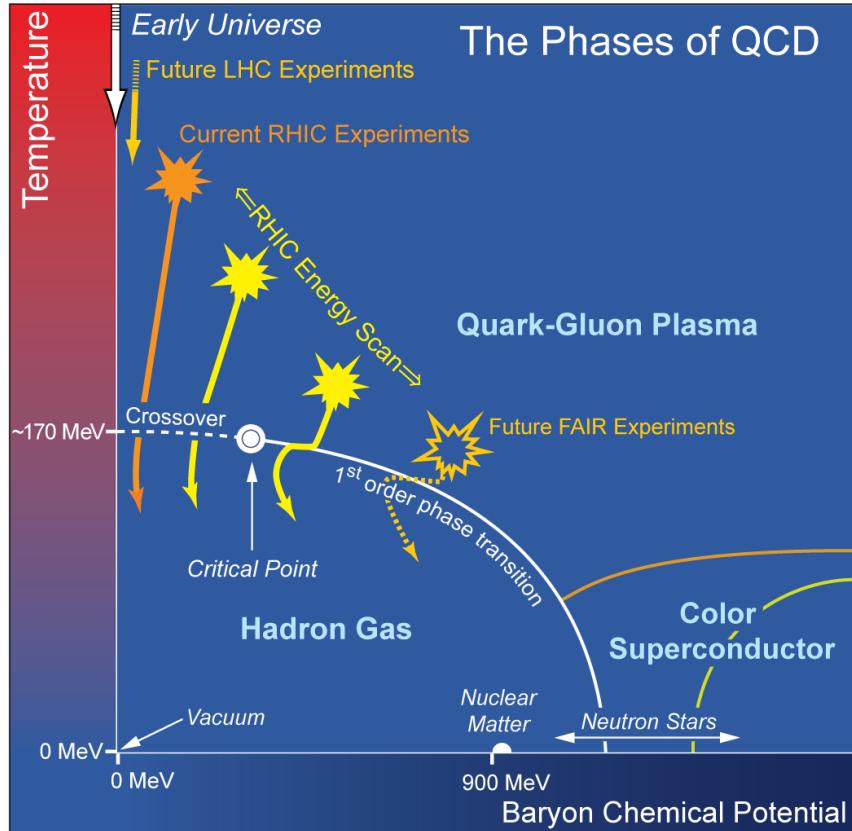
High  $p_T$  ( $> 2 \text{ GeV}/c$ ): number of quarks ordering

s-quark hadron: smaller interaction strength in hadronic medium

light- and s-quark hadrons: similar  $v_2$  pattern

**=> Collectivity developed at partonic stage!**

# The QCD Critical Point



- LGT prediction on the transition temperature  $T_c$  is robust.
- LGT calculation, universality, and models hinted the existence of the critical point on the QCD phase diagram\* at finite baryon chemical potential.
- Experimental evidence for either the critical point or 1<sup>st</sup> order transition is important for our knowledge of the QCD phase diagram\*.

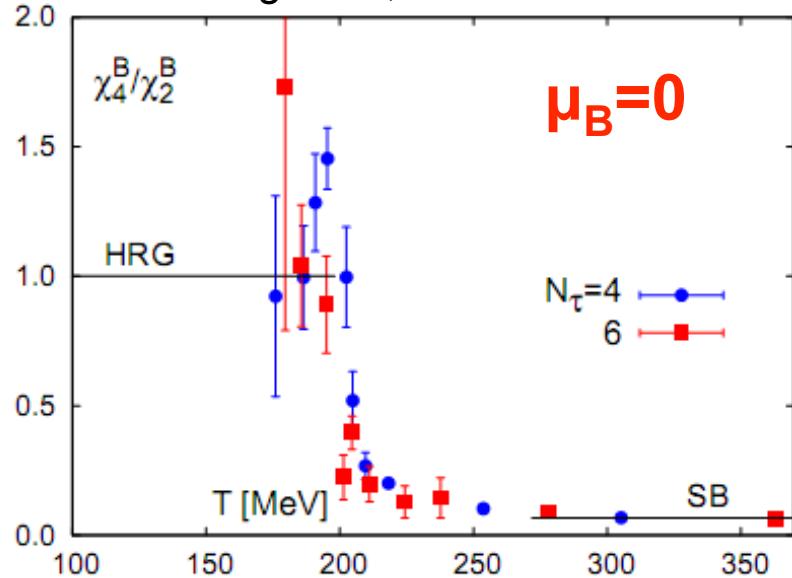
\* *Thermalization has been assumed*

M. Stephanov, K. Rajagopal, and E. Shuryak, PRL **81**, 4816(98); K. Rajagopal, PR **D61**, 105017 (00)

<http://www.er.doe.gov/np/nsac/docs/Nuclear-Science.Low-Res.pdf>

# Susceptibilities and High Moments

M. Cheng *et al.*, arXiv: 0811.1006



(I) Susceptibilities from the lattice QCD calculations

$$\chi_2^X = \frac{1}{VT^3} \langle \delta N_X^2 \rangle$$

$$\chi_4^X = \frac{1}{VT^3} \left[ \langle \delta N_X^4 \rangle - 3 \langle \delta N_X^2 \rangle^2 \right]$$

$$\chi_4^X / \chi_2^X \Rightarrow \kappa^X$$

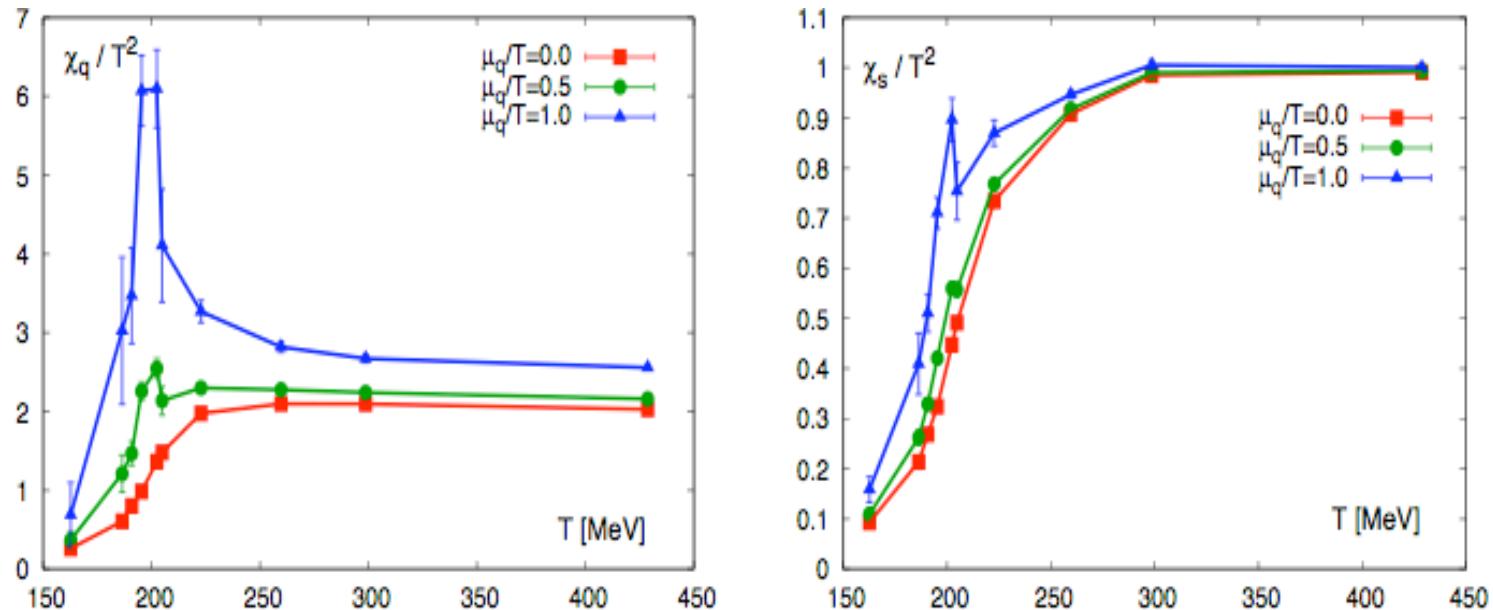
(II) At the CP at finite value of  $\mu_B$ , the power of the correlation length of the system is proportional to the order of the moments:

$$\langle (\delta N)^2 \rangle \propto \xi^2, \quad \langle (\delta N)^3 \rangle \propto \xi^{4.5} \quad \langle (\delta N)^4 \rangle - 3 \langle (\delta N)^2 \rangle^2 \propto \xi^7$$

Increase of the ***non-Gaussian*** fluctuation at the critical point

M. Stephanov, PRL **102**, 032301(09)

# Observables: $\chi_q$ , $\chi_s$



## Event by Event:

1. net-proton Kurtosis  $K_p(E)$
2. two proton correlation function  $C_2(E)$
3. ratio of the d/p
4. ratio of K/p

$$K_p = \frac{\langle N_p^4 \rangle - 3\langle N_p^2 \rangle^2}{\langle N_p^2 \rangle}$$

*M. Cheng et al., PRD79, 074505(09);arXiv:0811.1006  
F. Karsch, INT, 08  
M. A. Stephanov, PRL102, 032301(09)*

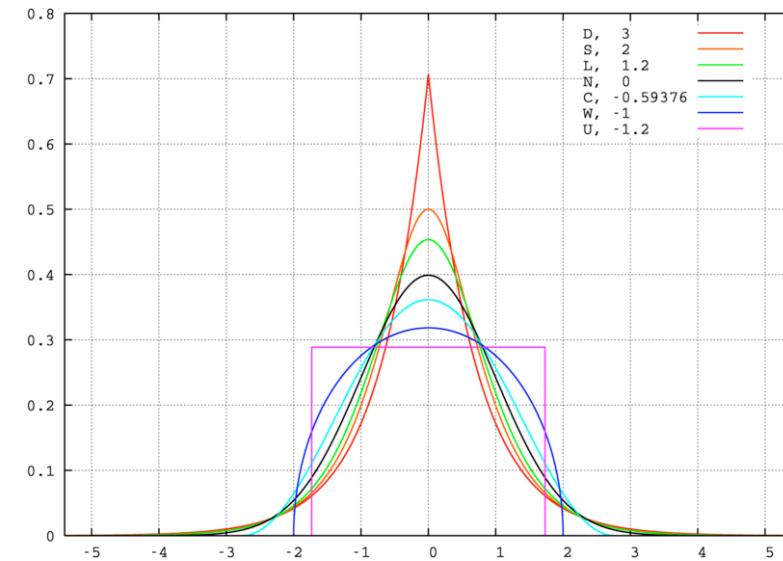
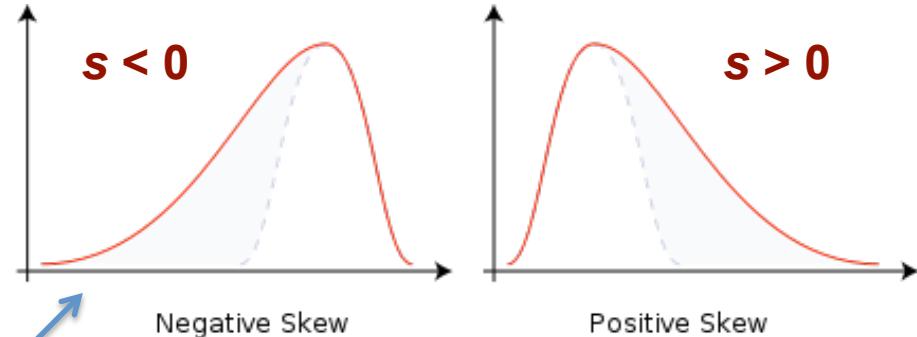
# Basics on Skewness and Kurtosis

**Mean:**  $M = \langle N \rangle$

**Variance:**  $\sigma^2 = \langle (N - \langle N \rangle)^2 \rangle$

**Skewness:**  $s = \frac{\langle (N - \langle N \rangle)^3 \rangle}{\sigma^3}$

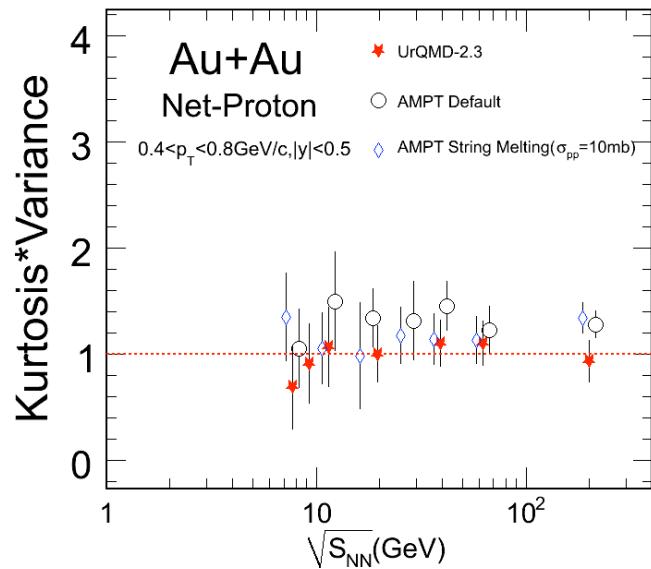
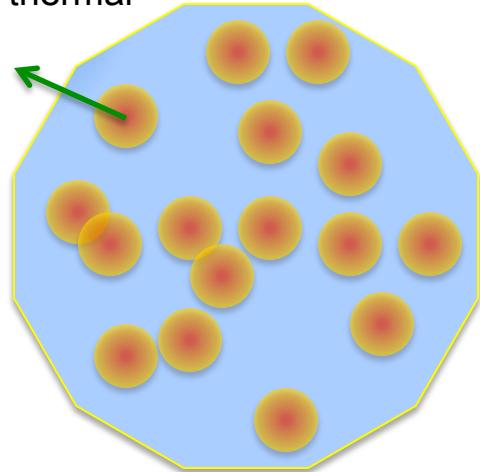
**Kurtosis:**  $\kappa = \frac{\langle (N - \langle N \rangle)^4 \rangle}{\sigma^4} - 3$



$s(\text{Gaussian}) = \kappa(\text{Gaussian})=0$ , ***Probe of non-Gaussian fluctuation.***

# Random Sources and Critical Point

Random thermal source  $i$



- (1) The sum of independent thermal sources is also a random thermal source. The multiplicity distribution is *Poisson* and follows the CLT.
- (2) In the absence of CP, it can be shown:

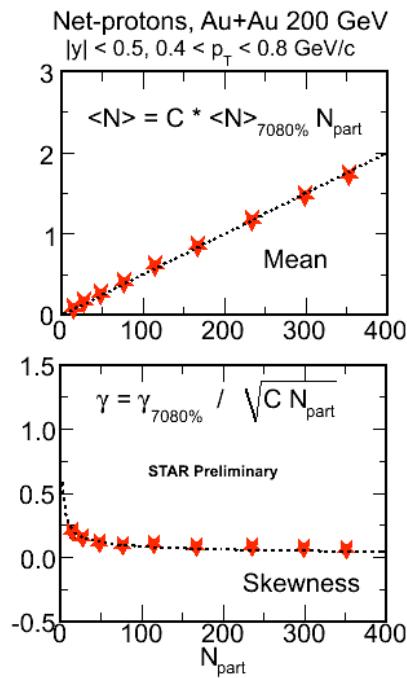
$$K * \sigma^2 = \text{const.}$$

$$S * \sigma = \text{const.}$$

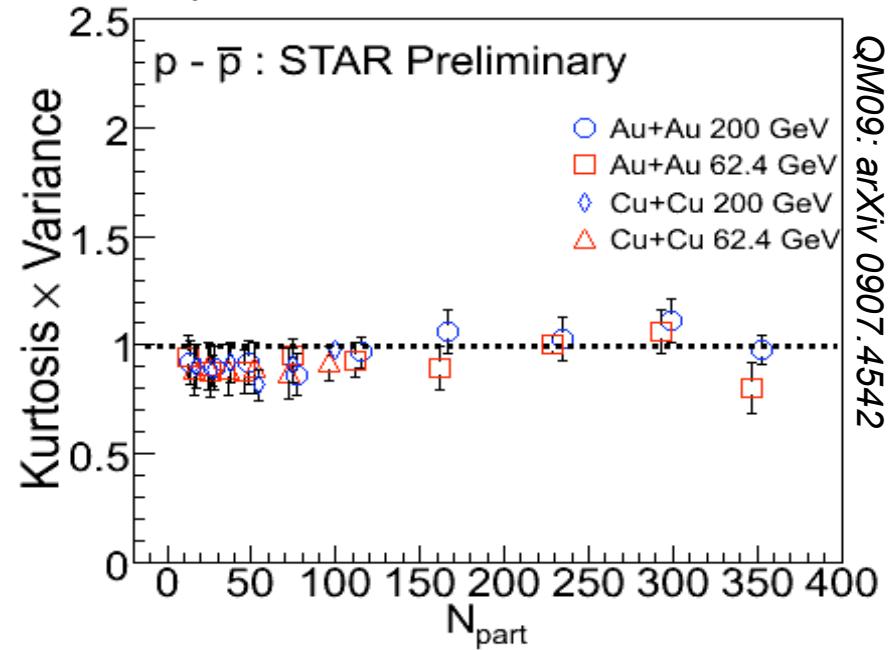
$$\begin{aligned} \text{Lattice results} &\propto \frac{\chi_4}{\chi_2} T^2 \\ &\propto \frac{\chi_3}{\chi_2} T \end{aligned}$$

- (3) Energy and centrality (volume) dependence of the non-Gaussian behavior => **Critical Point!**
- (4) Extract thermodynamic **properties of the medium!**

# Higher Moments Analysis (BES)



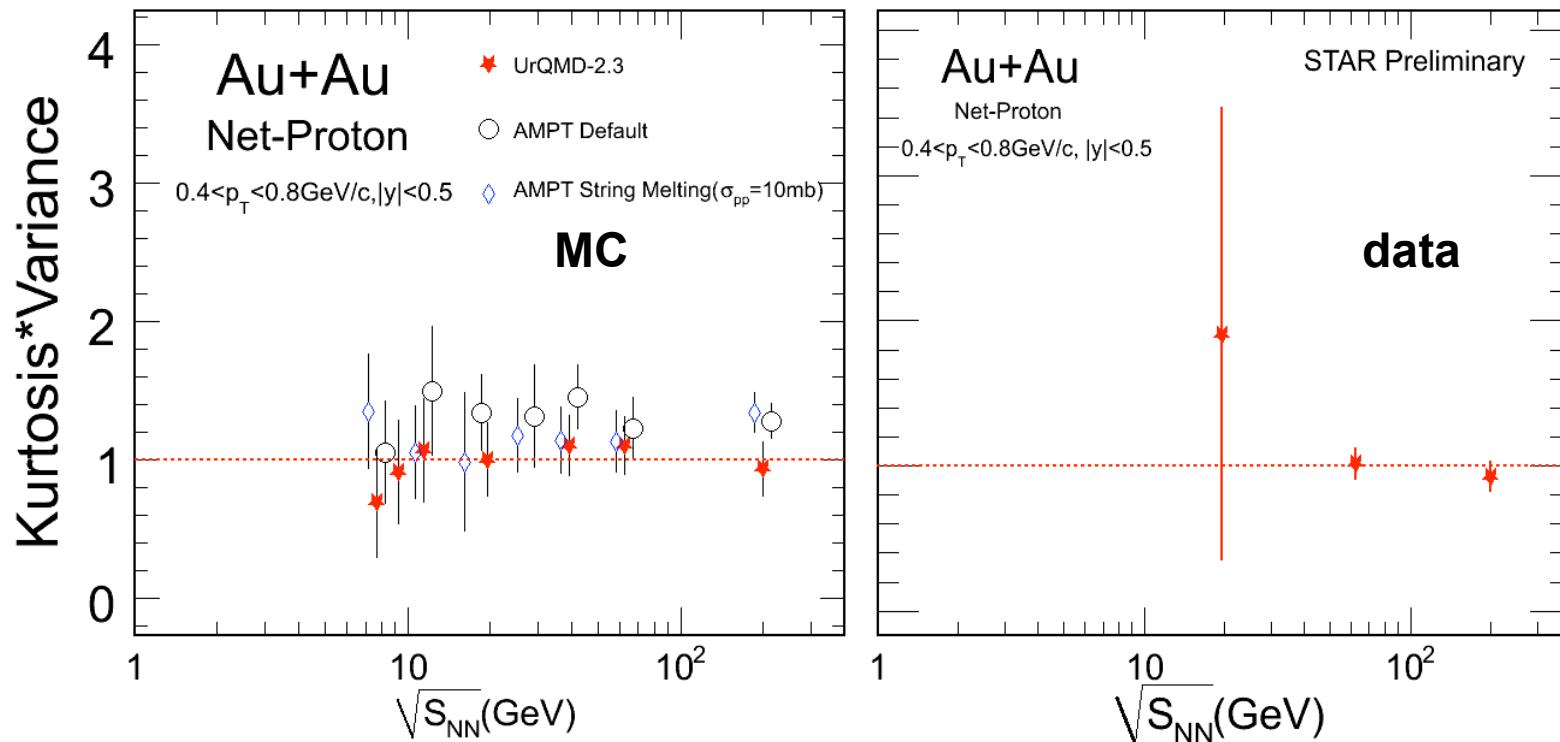
STAR Preliminary, QM09



- 1) Higher moments are more sensitive to QCD critical point related fluctuation.
- 2) The 4<sup>th</sup> moment, Kurtosis, is directly related to the corresponding thermodynamic quantity: susceptibility of conserved quantum numbers such as Baryon number and strangeness.

# $\kappa \cdot \sigma^2$ vs. Collision Energy

$$\kappa * \sigma^2 = \sum_{i=1}^k \sigma_i^2 / \sum_{i=1}^k [1 / \kappa_i]$$



- Energy and centrality dependence of  $\kappa \cdot \sigma^2$
- Flat results from models without the CP

## **QCD Phase Boundary and the Critical Point**

# **Summary**

- 1) Beam energy scan (BES) at RHIC is an important/necessary step forward for exploring the QCD phase diagram with high-energy nuclear collisions
- 2) LGT predicts a spike at finite value of  $\mu_B$  indicating the existence of CP
- 3)  $\kappa \times \sigma$  for net-protons are consistent with unity for the beam energy range:  $\sqrt{s_{NN}} = 200 - 62.4 - 19.6$  GeV at RHIC.  
Other conventional observables should also be studied.

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